Evaluation methods on manure exposure from liquid manure injection tools

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Rahman, S., Chen, Y., Zhang, Q. and Lobb, D. 2005. Evaluation methods on manure exposure from liquid manure injection tools. Canadian Biosystems Engineering/Le génie des biosystèmes au Canada 47: 6.9 - 6.16. Laboratory and field studies were conducted to explore evaluation methods on manure exposure (refer as to manure being not covered by soil, but exposed to the air) for liquid manure injection tools. The laboratory study was conducted in an indoor soil bin with three sweeps (small, medium, and large) at three injection depths (50, 100, and 150 mm), two tool forward speeds (0.6 and 1.4 m/s), and two soil moisture contents (14 and 18%). Soil surface profiles measured with a laser profiling system were used to define two parameters, risk and beneficial factors, as well as manure exposure and soil cover indices, to assess the risk for manure exposure following liquid manure injection. These parameters indicated that a larger sweep operating at greater injection depth and lower forward speed resulted in low risk for manure exposure on the soil surface. Soil moisture content did not significantly affect the manure exposure. The field study was conducted with a commercial injector consisting of 13 sweep injection tools in a clay soil at three manure application rates (28, 56, and 112 m3/ha) and an injection depth of 100 mm. Following the manure injection, line-transect and image analysis methods were used to quantify the percentage of the surface area covered with manure (manure cover), and the odour concentration and emission rate were determined by a wind tunnel and a dynamic dilution olfactometer. The results showed that manure cover increased at an increased manure application rate. No statistically significant effect of manure application rate on odour concentration was observed, and the odour data were not correlated to the manure cover data. Keywords: manure, injection, exposure, rate, depth, speed, moisture, profile, odour.

INTRODUCTION

With the expansion of the swine industry across North America, there is a growing concern in regard to odour and nutrient losses from land application of manure. Although manure injection is considered the most effective mitigation approach to minimise the nuisance caused by odour (Pain et al. 1991), significant odour emissions can still occur following liquid manure injection operations (Moseley et al. 1998; Chen et al. 2001). This occurrence is the result of the injected manure being not covered by soil and being exposed to the air (hereafter referred to as manure exposure) (Chen and Tessier 2001). Manure exposure may contribute to nutrient losses through ammonia volatilization and surface runoff (Huijsmans et al. 2003). Minimal manure exposure should be the ideal result of liquid manure injection, since the primary objective of injection is to place manure into the soil and cover it with a layer of soil.

There are different kinds of injection tools, such as knife, chisel, sweep, and disc. Among these, sweeps are widely used for manure injection because they provide a more even distribution of manure (Chen 2002). Manure exposure following injection likely depends on injection depth, manure application rate, tool operating parameter, and soil conditions as well as the combined effects of any of these. Soil profile also affects manure exposure. For example, a smoother soil profile may provide a better soil cover for the injected manure, minimising manure exposure.

Little research has been done in the past in terms of measuring manure exposure on the soil surface. Chen (2002) measured the manure exposure of open soil furrows only, and Hultgreen and Stock (1999) performed only visual inspections of the manure exposed on soil surface. Line-transect methods have been widely used to estimate residue cover on soil surface (Sloneker and Moldenhauer 1977) and they may be used to
estimate manure exposure on the soil surface. Image analysis has also been used to estimate percent residue cover with less human error (Han and Hayes 1990; Chen et al. 2004). As microcomputer-based imaging systems have become widely available at low cost, this method may also be applied for estimating manure exposure.

In the past, most of the soil profile studies (McKyes and Maswaure 1997; Raper and Grift 2002) have been conducted on tillage tools. The importance of soil profile associated with manure injection has been ignored or overlooked. Most of the studies on performance evaluations of manure injection have focused on manure distribution in soil (Rahman et al. 2004), crop response to different injection methods (Hanna et al. 2000; Chen and Samson 2002), and draft of tools (Rahman et al. 2001; Laguë 1991). Little research has been done on measuring and quantifying manure exposure following liquid manure injection. Past research (Hanna et al. 2000; Chen et al. 2001; Rahman et al. 2001; Oh et al. 2004) showed that odour measurements were costly and time consuming and that the data were highly variable. Chen et al. (2001) indicated that ammonia volatilization and odour emission from the soil surface following manure application seemed proportional to the amount of manure exposed on the soil surface. Therefore, it is rational and necessary to establish the relationship between manure exposure and the odour emission.

The objective of this study was to develop methods that can be used to evaluate the performance of liquid manure injection tools in terms of manure exposure. The specific objectives were: i) to use soil profile characteristics to quantify the risk of manure exposure as affected by injection depths, tool forward speeds, and soil moisture content; ii) to quantify surface manure exposure following liquid manure injection as influenced by manure application rate; iii) to explore the correlations between manure exposure and the corresponding odour level; and iv) to adopt the line-transect and image analysis methods to measure manure exposure following injection.

**MATERIALS and METHODS**

**Laboratory study**

**Description of the test facility and injection tools** Laboratory tests of liquid manure injection tools were conducted in an indoor soil bin (1.5 m wide, 15 m long, and 0.6 m deep) with a loamy sand soil, located in the Department of Biosystems Engineering at the University of Manitoba, Winnipeg, Canada. To obtain the desired soil moisture contents, water was sprayed over the soil and left to infiltrate for 24 h throughout the tests. Then the soil was roto-tilled at a greater depth than the maximum experimental design depth. The last step for soil preparation was to level and compact the soil with a 162 kg smooth flat roller. After soil preparation, the soil dry bulk density was approximately 1.2 Mg/m³. The same procedures for the soil preparation were used between tests. Three commercially available sweep injection tools (small, medium, and large sweeps) (Fig. 1a, 1b, 1c) were tested. The widths of the small, medium, and large sweeps were 225, 255, and 330 mm, respectively. The length of all the sweeps was 220 mm and the rake angle of the small, medium, and large sweep were 16, 18, and 20º, respectively.

**Experimental design** The sweeps were tested in the soil bin using a completely randomised factorial (3 × 3 × 2 × 2) experiment (three replications). The treatments included all combinations of three sweeps, three injection depths (50, 100, and 150 mm), two tool forward speeds (0.6 and 1.4 m/s), and two soil moisture contents (14 and 18%).

**Measurements** After each test run, a laser soil profiler, LPS sensor (INO, Quebec, QC) was moved over the disturbed soil surface to measure the soil surface profile on the plane perpendicular to the tool travel direction. For each test run, three measurements of the soil profile were taken at random locations along the length of the soil bin. Measurements were concentrated in the area around the centre line of tool path where manure is to be injected (Fig. 2a, 2b). This area is described as a “risk zone” for manure exposure. The distance between the lowest soil profile and the original soil surface along the centre of the tool path was measured. The lateral distance of the furrow opening along the original soil surface was also measured. These measurements were selected to assess the potential impact of soil surface profile on manure exposure, as discussed below. Due to the limitation of the indoor test facility used, no manure was applied during this laboratory study. This had little or no effect on the study of the soil surface profiles, since soil surface profile is mainly affected by the soil cutting action of the tool.

**Field study**

Description of the field injection unit Since none of the sweeps used for the laboratory study was available for the field study, a commercial field injection unit (Fig. 3) had to be used although its sweeps were different from those used in the laboratory study. The 13 sweeps were spaced 540 mm apart and were arranged on a 7-m tool bar in two ranks (7 sweeps in the
Fig. 2. Diagram showing a typical soil surface profile: (a) negative-type and the definitions of risk factor \( (F_r) \) and the furrow opening \( (W) \); (b) positive-type and the definition of beneficial factor \( (F_b) \).

Fig. 3. Field injection unit with 13 narrow sweeps in two ranks (seven sweeps in the first rank and six sweeps in the second rank).

Site description and experimental design
The field manure injection trial was conducted in a clay soil at St. Agathe, Manitoba in October 2002. Before the manure injection, the stubble field was tilled with a typical field cultivator. A completely randomised experimental design (four replicates) was used with three manure application rates: \( R_1=28 \), \( R_2=56 \), and \( R_3=112 \) m\(^3\)/ha at an injection depth of 100 mm. Thus, a total of 12 plots was required for the field trial. One pass was made with the injection unit in each plot and the plot size was 7 m width by 10 m long.

Measurements
Five soil cores (150 mm deep and 52 mm diameter) were collected from random locations within the field before the field trial was conducted. Soil samples were weighed, oven dried for 24 h at 105°C, and re-weighed to determine the gravimetric soil moisture content and soil dry bulk density. The mean ambient temperature and relative humidity of the ambient air were measured with a thermometer.

Two methods, line-transect (LT) and image analysis (IA), were used to estimate the manure cover. In the IA method, a simple quadrant (1000 mm wide by 1000 mm long) (Fig. 4a) was placed randomly over the plot immediately following the manure injection. A digital image (Fig. 4b) was quickly taken over the simple quadrant. Images were downloaded to a personal computer and were converted to 680 by 480 pixels bitmap (BMP) images. The BMP images were processed with the ASSESS (Lamari 2002). Manure cover (the percentage of the surface area covered with manure) was determined using the ASSESS program, which could separate the surface covered by manure based on hue (or saturation) (Fig. 4c), and the area of the manured surface was selected digitally using a user defined threshold. In the LT method, a mesh quadrant (700 mm wide by 800 mm long) with 110 grids (70 mm wide by 70 mm long) was used. To compare this method to the IA method, the mesh quadrant was quickly placed inside the simple quadrant (Fig. 4a) after the digital image was taken. The number of intersections that were directly over the surface covered by manure was counted. Manure cover was determined using:

\[
C_m = \frac{N_m}{N_t} \times 100
\]

where:
- \( C_m \) = manure cover (%),
- \( N_m \) = number of intersections over the manured surface,
- \( N_t \) = total number of intersections in the mesh quadrant.

Immediately after the manure injection, a portable wind tunnel (Fig. 5a) was placed on the soil surface to collect odorous air samples from the soil surface. The wind tunnel consisted of a carbon filter, a fan, a main chamber, and a sampling outlet (Fig. 5b). A complete description of the wind tunnel can be found in Cicek et al. (2003). The bottom of the main chamber (0.25 m high from the ground) was open to the soil surface and
covered an area of 0.3 m² (0.75 m long by 0.4 m wide). An average wind speed of 0.3 m/s was maintained in the main chamber. A vacuum chamber (AC’SCENT, St. Croix Sensory, Inc., Stillwater, MN) was connected to the outlet of the main chamber to collect the odorous air in a 10-L Tedlar bag. Sampling was performed at four random locations in each plot. Thus a total of 48 (12 × 4) samples was collected. Prior to the manure injection, four background air samples of the unmanured soil surface were also taken. After the field injection trial, four air samples were taken from the surface of the manure storage using the same wind tunnel equipped with a floating device. Samples were brought back to the laboratory for subsequent analysis by using an olfactometer (AC’SCENT, St. Croix Sensory, Inc., Stillwater, MN) within 24 h. Odour concentrations were measured by odour units (OU/m³) using a triangular forced choice method with six panellists. The odour concentrations were then converted to an odour emission rate as:

\[ E = \frac{C \times V \times A_c}{A_s} \]  

where:
- \( E \) = odour emission rate (OU m⁻² s⁻¹),
- \( C \) = odour concentration (OU/m³),
- \( V \) = velocity of air in the tunnel (m/s),
- \( A_c \) = cross-sectional area of main chamber (m²), and
- \( A_s \) = surface area covered by the tunnel (m²).

**Data analyses**

Analysis of variance (ANOVA) was performed to examine the effects of experimental factors and their interactions. As the interaction effects were not significant, the means of main effects were compared using the Duncan’s multiple range tests (Steel and Torrie 1997) at a significance level of \( P=0.1 \).

**RESULTS and DISCUSSION**

**Laboratory study**

**Pattern of the soil surface profile** Injection tools loosened the soil and moved the soil laterally, forming a sinusoidal shaped soil surface profile with a depression along the centre of the tool path and two mounds on the sides (Figs. 2a, b). Mounds on either side of the furrow may affect infiltration, runoff velocities, and plant growth, as often observed from tillage tools (Lehrsch et al. 1988). In the case of manure injection, the mounds may or may not help cover the injected manure, but they may cause burial of plants and crop residue, and required an extra tillage operation for seedbed preparation. As manure is replaced along the centre line of the tool path, the centre region of the soil profile is of interest for evaluating manure exposure.

Two typical types of soil surface profiles were observed in this study, the negative-type, where the furrow opening is located below the original soil surface (Fig. 2a), and the positive-type, where the furrow opening is located above the
original soil surface (Fig. 2b). The positive-type soil profile is considered more favourable for minimising manure exposure because more soil is located on the top of the injected manure. However, the negative-type profile does not necessarily pose manure exposure problems, depending on how deep the manure is injected in the soil.

A “risk” factor \( (F_r) \) and a “beneficial” factor \( (F_b) \) were defined as the distance between the original soil surface and the lowest position of the furrow opening profile. The value of \( F_r \) is equal to zero for a positive-type profile and that of \( F_b \) is equal to zero for a negative-type profile. The risk of manure exposure can also be assessed by the width of the soil opening (\( W \)) at the original soil surface. The value of \( W \) is equal to zero for a positive-type profile. In this study, the recorded risk factor, \( F_r \), ranged from 0 to 37 mm, while a smaller range for the beneficial factor, \( F_b \) (0 to 28 mm) was observed. The value of furrow opening \( W \) was up to 181 mm. The smaller values of \( F_r \) and \( W \), and the larger values of \( F_b \), potentially indicate better performance of an injection tool under a given condition.

**Manure exposure index \( (I_m) \) and soil cover index \( (I_s) \)** Field efficiency of an injection tool needs to be evaluated taking not only risk and beneficial factors in consideration, but also the injection depth at which the tool operates. Greater injection depth means more power requirement associated with the soil cutting (Rahman and Chen 2001). Therefore, manure exposure and soil cover indices were introduced to reflect the possibility of manure exposure on the soil surface in relation to the injection depth, based on soil profile characteristics. The manure exposure index is defined as the ratio of risk factor and injection depth, as:

\[
I_m = \frac{F_r}{d} \times 100
\]

where:

- \( I_m = \) manure exposure index (%)
- \( d = \) injection depth (mm).

The soil cover index is defined as the ratio of the beneficial factor and injection depth as:

\[
I_s = \frac{F_b}{d} \times 100
\]

Values of \( I_m \) and \( I_s \) were calculated by Eqs. 3 and 4, and their statistical analysis results are show in Table 1. In general, the smaller the values of \( I_m \) and the larger the values of \( I_s \), the better the injection tool performance in terms of manure exposure.

**Effect of tool size on manure exposure** Significant effects of sweep size on soil cover index \( (I_s) \) were observed, with the large sweep better covering the injected manure than the medium and small sweeps (Table 1). The data of \( F_s \), \( F_r \), \( W \), and \( I_m \) indicated that the large sweep also has a lower risk of manure exposure, when compared to the other two sweeps. However, the trends were not significantly different. A larger sweep tool generally lifted more soil and resulted in more soil being above the original soil surface. Selection of injection tool should also be based on other criteria such as tool draft. Notice that larger tool size would result in higher draft and therefore require more power for the injection operation (Rahman and Chen 2001).

**Effects of injection depth on manure exposure** The result of the \( F_s \) was consistent with that of the \( F_r \). The value of \( F_s \) was higher and that of \( F_r \) was lower at the 150 mm depth than at the 50 and 100 mm depths (Table 1). The lower value of \( W \) at 150 mm further confirmed the better performance of injection at this depth. Injection depth had no effect on \( I_m \), while again, the 150 mm depth had the lowest \( I_m \), followed by the 100 mm and then 50 mm. At a greater depth, more soil-tool interactions occur and soil particles stick together rather than throwing laterally, creating smaller furrow openings. Notice that greater injection depth would result in higher draft of the injection tool (Rahman and Chen 2001).

**Table 1. Effects of sweep size, injection depth, tool forward speed, and soil moisture content on the soil surface profile characteristics.**

<table>
<thead>
<tr>
<th>Treatment</th>
<th>Beneficial factor, ( F_b ) (mm)</th>
<th>Risk factor, ( F_r ) (mm)</th>
<th>Furrow opening, ( W ) (mm)</th>
<th>Soil cover index, ( I_s )</th>
<th>Manure exposure index, ( I_m )</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Sweep size</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Small</td>
<td>3 a*</td>
<td>14 a</td>
<td>65 a</td>
<td>0.02 b</td>
<td>0.18 a</td>
</tr>
<tr>
<td>Medium</td>
<td>3 a*</td>
<td>14 a</td>
<td>72 a</td>
<td>0.03 b</td>
<td>0.22 a</td>
</tr>
<tr>
<td>Large</td>
<td>5 a</td>
<td>11 a</td>
<td>61 a</td>
<td>0.07 a</td>
<td>0.16 a</td>
</tr>
<tr>
<td><strong>Injection depth (mm)</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>50</td>
<td>2 b</td>
<td>15 a</td>
<td>74 a</td>
<td>0.04 a</td>
<td>0.30 a</td>
</tr>
<tr>
<td>100</td>
<td>3 b</td>
<td>15 a</td>
<td>77 a</td>
<td>0.03 a</td>
<td>0.15 b</td>
</tr>
<tr>
<td>150</td>
<td>7 a</td>
<td>10 b</td>
<td>47 b</td>
<td>0.05 a</td>
<td>0.06 c</td>
</tr>
<tr>
<td><strong>Tool forward speed (m/s)</strong></td>
<td>0.6</td>
<td>7 a</td>
<td>33 b</td>
<td>0.07 a</td>
<td>0.11 b</td>
</tr>
<tr>
<td></td>
<td>1.4</td>
<td>0 b</td>
<td>19 a</td>
<td>0.00 b</td>
<td>0.27 a</td>
</tr>
<tr>
<td><strong>Soil moisture content (%)</strong></td>
<td>14</td>
<td>3 a</td>
<td>13 a</td>
<td>0.03 a</td>
<td>0.19 a</td>
</tr>
<tr>
<td></td>
<td>18</td>
<td>4 a</td>
<td>14 a</td>
<td>0.05 a</td>
<td>0.18 a</td>
</tr>
</tbody>
</table>

* Means followed by the same letter in each column and each treatment are not significantly different \((P = 0.1)\) according to Duncan’s multiple range test.
Effects of tool forward speed on manure exposure
Increasing tool forward speed from 0.6 to 1.4 m/s significantly increased the values of $F_r$, $W$, and $I_{m}$, and decreased the values of $F_l$ and $I_{r}$ (Table 1). It is expected that higher tool forward speed moves more soil from the centre of the tool to the sides, forming a larger furrow opening. The results clearly demonstrated that the lower speed has less risk for manure exposure. Tools working at a higher speed also throw more soil laterally, resulting in higher surface roughness and higher power requirement (Rahman et al. 2005).

Effects of soil moisture content on manure exposure The results showed that increasing soil moisture content from 14 to 18% was slightly better for covering manure (Table 1), although the effect was not statistically significant. This trend is inconsistent with the results observed by Raper and Grift (2002) where low soil moisture content contributed to increased soil profile above the original surface. At higher moisture content, soil aggregates are more adhesive and resistant to lateral movement, while at lower moisture content the soil has higher friability and lower plasticity (McKyes 1985). As a result, higher soil disturbance is often found in dryer soil.

Table 2. Manure cover, odour concentration, and odour emission at the soil surface following manure application at different rates and background values.

<table>
<thead>
<tr>
<th>Treatment</th>
<th>Manure cover (%)</th>
<th>Odour concentration (OU/m³)</th>
<th>Odour emission (OU · s⁻¹)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Mean (SD)</td>
<td>Mean (SD)</td>
</tr>
<tr>
<td>Application rate (m³/ha)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>R1 = 28</td>
<td>8 c</td>
<td>1053 a* 196</td>
<td>105 a 20</td>
</tr>
<tr>
<td>R2 = 56</td>
<td>12 b</td>
<td>939 a 298</td>
<td>94 a 30</td>
</tr>
<tr>
<td>R3 = 112</td>
<td>22 a</td>
<td>1044 a 245</td>
<td>104 a 24</td>
</tr>
<tr>
<td>Initial (background)</td>
<td>0</td>
<td>670 56</td>
<td>67 6</td>
</tr>
<tr>
<td>Manure storage</td>
<td>100</td>
<td>1616 933</td>
<td>162 93</td>
</tr>
</tbody>
</table>

* Means followed by the same letter in each column are not significantly different (P = 0.1) according to Duncan’s multiple range test.

Field study

Background information At the time of field trials, the soil moisture content was 30% (dry basis) which was adequate for performing field operations in that soil. Since the field was tilled before manure injection, the soil was quite loose, as indicated by the dry soil bulk density (0.82 Mg/m³). The mean ambient air temperature and relative humidity at the time of field trials were –2°C and 43%, respectively.

Correlation between the line-transect (LT) and image analysis (IA) The results showed that the line-transect (LT) and image analysis (IA) methods have a reasonably good correlation ($r = 0.7$) (Fig. 6). It is uncertain as to which method represents the true value of manure cover, since there is no standard method to be used as a reference. The LT has been widely used for surface residue cover measurements, while its application to manure cover measurements is fairly new. As mentioned earlier, the LT method is subjective and the quantification depends on the judgement of the observer. The IA method depends on the extent of the difficulties in differentiating the colour of bare soil from that of the manured soil. As well, the presence of stubble residue on the soil surface could also affect the results of image analysis. The LT method would have to be used when the required electronic equipment for imaging analysis is not available.

Effects of manure application rate on manure cover The effect of the manure application rate on manure cover was assessed with the data from the IA. The measured manure cover varied from 5 to 33%. It was sometimes visually observed that the manure placed in the furrows came up to the soil surface. The slow infiltration of the clay soil was one of the contributing factors. It was also observed that the soil furrow was partially closed before manure was placed into the furrow, while the tool was in operation. Modifying the position of the manure drop tube relative to the tool would resolve this problem. The manure cover was significantly affected by the manure application rate (Table 2). At the R1 application rate, the manure cover was 8%, indicating that 8% of the soil surface was covered by manure. As the application rate increased from R1 to R2 and from R2 to R3, the manure cover increased to 12 and 22% (Table 2), respectively. The 22% manure cover was rated as poor injection tool performance by Hultgreen and Stock (1999).

Effects of application rate on odour concentration The background concentrations measured at the surface of the manure storage and at the soil surface prior to manure injection were 1616 and 670 OU/m³, respectively (Table 2). These values represented correspondingly the situations of 100 and 0% manure cover. The odour concentrations from the treatment plots were between those from the backgrounds, as expected. The odour concentrations obtained in this study are higher when compared with the results from Hanna et al. (2000), Chen et al. (2001), and Oh et al. (2004) for liquid swine manure injection. The high odour

Fig. 6. Comparison of the line-transect and the image analysis methods for manure cover measurements.
concentrations could be attributed to the cold weather during the field trials. Sommer and Hutchings (2001) observed that in cold weather, odour stayed near the ground surface. No statistically significant differences in odour concentration were observed between treatments due to the highly variable nature of odour measurements, although a large number of odour samples were taken (16 samples per treatment). This highlighted the need for more samples taken at the soil surface to get a good estimate of the odour concentration. Rahman et al. (2001) also reported that the effect of manure application rate on odour was not significant. Odour emission rates were calculated according to Eq. 2 and the results are presented in Table 2. The values of odour emission were one-tenth those of odour concentration. Similar to the odour concentration, the effect of manure application rate on odour emission rate was not significant.

CONCLUSIONS

The proposed parameters, including risk and beneficial factors, as well the manure exposure and soil cover indices, can be generated from soil surface profile characteristics. These parameters can be used as the performance indicators of liquid manure injection tools, since data of soil profile are available in the literature for many types of tools.

Tests on sweep-type tools on the aforementioned parameters showed that as compared with the medium and small sweeps, the large sweep could be the better choice for minimising manure exposure caused by the soil furrow opening. However, its higher power requirement associated with soil cutting should be taken into consideration. The 150 mm injection depth would be the best in terms of minimising manure exposure. However, a fairly high power will be required for the tool cutting at this depth according to the previous research. The 100 mm injection depth, showing a smaller manure exposure index than the 50 mm depth, could be selected when the power of the tractor is limited. Lower tool travel speed is suggested as it results in less risk of manure exposure. Soil moisture content at the studied range did not have any significant impact on manure exposure.

Both the line-transect and imaging analysis were fairly easy to use. Since there is no standard measurement method to be used as a reference, it is uncertain as to which method represents the true value of the manure cover. Imaging analysis, with less human error, can be considered more accurate. As the line-transect method is reasonably correlated to imaging analysis ($r = 0.7$), line-transect may be used when the electronic equipment for imaging analysis is not available.

The manure cover was significantly affected by manure application rate. At the manure application rate of 28 m$^3$/ha, 8% of the soil surface was covered by manure. When the application rate was doubled, the manure cover increased up to 22%. Effects of manure application rate on odour level were not detected due to the highly variable data. Also there were no correlations between manure cover and the corresponding odour level, which was unexpected. There is a need for further research on relationships between manure cover and odour level.

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REFERENCES


Rahman, S., Y. Chen and D.A. Lobb. 2005. Soil movement resulting from sweep-type manure injection tools (Accepted for publication in *Biosystems Engineering*).


